Validation of multi-physics integrated procedure for the HCPB breeding blanket

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Abstract

The wide range of requirements and constraints involved in the design of nuclear components for fusion reactors makes the development of multi-physics analysis procedures of uttermost importance. In the framework of the European DEMO project, the Karlsruhe Institute of Technology (KIT) is dedicating several efforts to the development of a multi-physics analysis tool allowing the characterization of breeding blanket design points which are consistent from the neutronic, thermal-hydraulic and thermal-mechanical point of view. In particular, a procedure developed at KIT is characterized by the implementation of analysis software only. A preliminary step for the validation of such a procedure has been accomplished using a dedicated model of the DEMO Helium Cooled Pebble Bed Blanket 4th outboard module. A global model representative of nuclear irradiation in DEMO and two local models have been set-up. Nuclear power deposition and the spatial distribution of its volumetric density have been calculated using Monte Carlo N-Particle transport code for the aforementioned models and compared in order to validate the procedure set up. The outcomes of this comparative study are herein presented and critically discussed.

Keywords: **DEMO reactor, Breeding Blanket, HCPB, multi-physics, coupling, design point**.

Introduction

Multi-physics analyses are of fundamental importance in the design of fusion relevant components and systems. Indeed, the design of a component for a fusion reactor must fulfil requirements and constraints which are of nuclear, material and safety kind and it must be therefore based on an iterative process which relies on the data acquired by neutronic, thermal-hydraulic and thermal-mechanical analyses. In a multi-physics design process, the neutronic analyses allow the estimation of loads for thermal-hydraulic and thermal-mechanical ones; data acquired from the analyses are then used to adjust the design of the component to safety, technical and economic requirements and constraints. The analysis cycle then restarts from a neutronic analysis and comes to an end only once all the constraints and requirements are fulfilled. In order to perform the described analysis cycle on a component, it is necessary to build a solid model of it, which is a digital representation of the geometry of the component itself. A major issue related to multi-physics analyses is due to the different solid model representation methods used by design codes. For what concerns neutronic calculation, very often Monte Carlo codes are adopted that, usually, use the Constructive Solid Geometry representation (CSG) by which the solid model is built by means of Boolean forms of primitive solids and algebraic half-spaces; thermal-hydraulic and thermal-mechanical analysis codes instead rely on solid models built using Boundary Representation method (BRep), through which a solid may be represented by a set of non-overlapping faces, whose union approximates the boundary of the solid [1]. The construction of two separate solid models of a component using different representation methods is a time consuming and error prone procedure which undermines the efficiency of the iterative design process. It has been, therefore, necessary to develop methodologies allowing the analyst to convert solid models and thus interconnect analysis codes during design cycle iterations. Karlsruhe Institute of Technology (KIT) has launched a research campaign within the framework of the EUROfusion programme for the development of a multi-physics design tool fulfilling the aforementioned necessity [2] [3]. Aim of the design tool is to perform preliminary multi-physics analysis cycles for the characterization of Breeding Blanket (BB) working points and the addressing of the key design issues. In order to realize a fast and reliable design cycle, a fast coupling approach and a simple circumscribed solid model to be analysed are required. A fast and simple coupling approach to be implemented in the design tool has been developed at KIT; indeed, it only relies on analysis software and thus provides direct interfaces between the codes used for neutronic, thermal-hydraulic and thermal-mechanical analyses, thus avoiding the use of intermediary utilities. First step of the approach is the import of a BRep solid model, previously realized with a CAD software, in ANSYS Design Modeler [4]; the solid model is then simplified and manipulated and finally exported into a Monte Carlo N-Particle transport code (MCNP) [5] suitable input exploiting the ANSYS code capability to convert a BRep model into a CSG one. In this way a simplified solid model representative of the component whose design has to be assessed can be achieved, which can be used in the design cycle with the appropriate choose of source and boundary conditions. Key requirements to assess the reliability of this kind of preliminary analysis tool are the validation of the coupling approach in terms of congruence of the converted solid models and the validation of the analysis method used for source and boundary conditions definition. The present work constitutes a first step in the assessment of such a reliability. To perform the validation of the preliminary analysis cycle, dedicated models of DEMO Helium Cooled Pebble Bed (HCPB) BB have been used. Two local models of the HCPB BB have been analysed and compared with a global model of the HCPB BB. First of all, volumes comparisons between the BRep solid models and the CSG solid models obtained after the conversion have been performed to assess the reliability of the coupling approach. Then, comparisons of nuclear power deposition data on the different models have been performed to validate the analysis method.

1. Validation procedure overview

A preliminary work for the validation of the coupling approach has been performed on the DEMO HCPB BB 2015 concept [6] [7] [8]. A BRep solid model of a radial-toroidal slice of the 4th outboard (OB4) module has been converted into an MCNP suitable input using the coupling approach as done in [2]. The same methodology has been also applied to a BRep solid model of the cap of the module. Using repeated structures capabilities of MCNP, the neutronic models of the cap and the slice have been used to build a CSG solid model of the full OB4 module. The obtained model of the module has been implemented in a full DEMO HCPB BB reference model developed by KIT [7]; as a result, a DEMO HCPB BB model having the OB4 module represented with full features has been achieved. The DEMO HCPB BB reference model with its neutron source, has been used to define local sources for the initial slice model and for the full OB4 module model. The three models have been then analysed to assess their consistency and evaluate the capability of the approach to map the spatial distribution of the nuclear power density deposition. All the nuclear quantities of interest have been evaluated by MCNP5 code using the FENDL-3.1 transport cross section libraries [9]. The procedure and a comparison of the results are herein discussed.

2. Reference Models

2.1 Slice model

A solid model of a slice extracted from the DEMO HCPB OB4 module has been imported in ANSYS Design Modeler. The slice (i.e. the fundamental unit of the breeding zone (BZ) of a module) is composed of half Be pebble bed, a cooling plate and half Li_4SiO_4 pebble bed. The whole slice is 3.275 cm thick in the poloidal direction, with a Cooling Plate (CP) of 0.500 cm thickness and the Be and Li_4SiO_4 half pebble beds of 2.000 cm and 0.775 cm respectively. Figure 1 shows an isometric projection of the SLICE BRep solid model in ANSYS Design Modeler, where the bodies which compose the solid model have been grouped in named selections according with their composition. The model has been simplified in ANSYS Design Modeler and exported in an MCNP suitable input using the coupling approach [2]. The simplified model obtained in ANSYS Design Modeler is shown in Figure 2. Moreover, reflective boundary conditions both on the poloidal and toroidal planes delimiting the model have been imposed to simulate the geometrical continuity in those directions [2]. The CSG solid model obtained, from now on the SLICE model, is shown in Figure 3 and Figure 4.

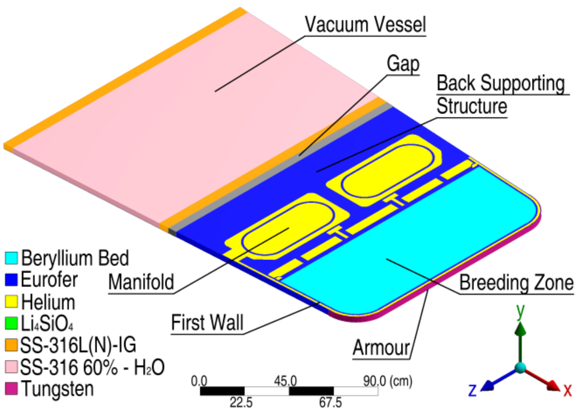

Figure 1. SLICE BRep solid model (isometric projection).

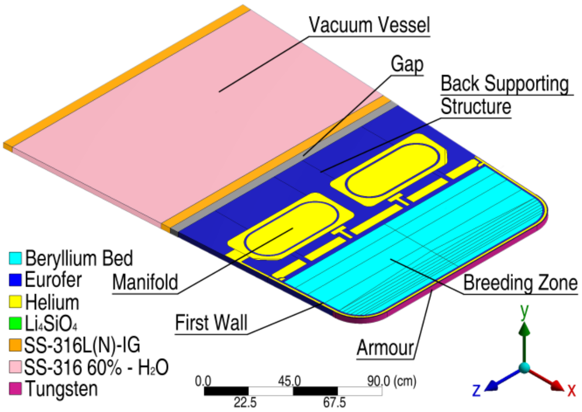

Figure 2. Simplified SLICE BRep solid model (isometric projection).

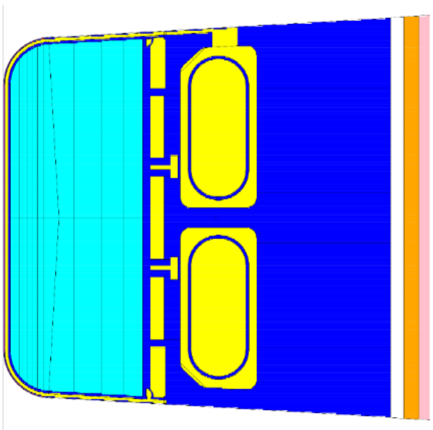

Figure 3. SLICE CSG solid model (radial-toroidal view).

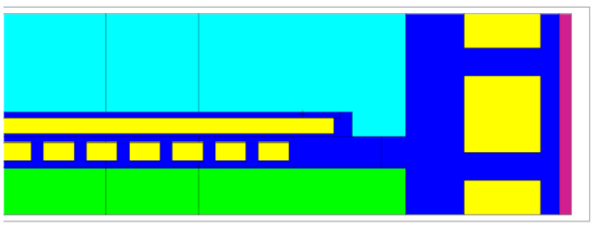

Figure 4. SLICE CSG solid model (radial-toroidal detail).

The volumes of the bodies of the original BRep solid model have been compared with the corresponding volumes of the SLICE CSG model, stochastically assessed by MCNP. A percentage difference of 0.0147% between the whole volume of the models has been assessed together with a mean of the absolute value of the relative difference per body/cell of 0.3165%.

2.1 CAP model

A solid model of the cap of DEMO HCPB BB OB4 module has been imported in ANSYS Design Modeler and the neutronic model CAP has been obtained as a result of the coupling approach application. The BRep solid model of the cap is shown in Figure 5 and Figure 6. The CAP neutronic model has been generated with the main purpose to serve as a geometric entity for the construction of the full OB4 module model (from now on MODULE model). The simplified BRep solid model of the cap and the obtained CSG solid model of the CAP are shown in Figure 7 and Figure 8.

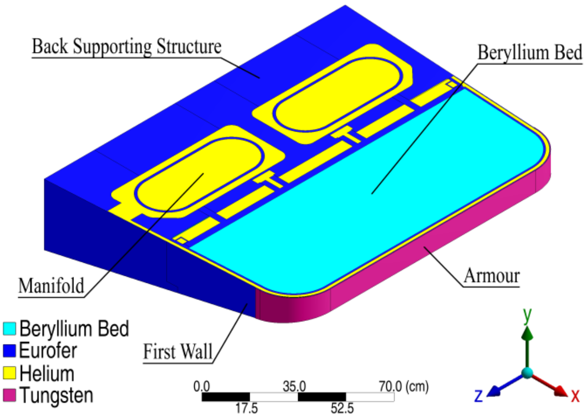

Figure 5. CAP BRep solid model (isometric projection).

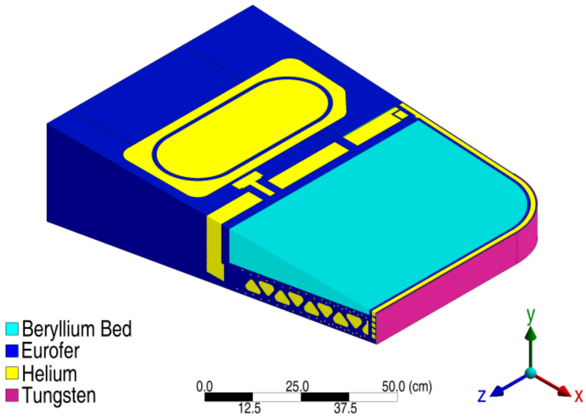

Figure 6. CAP BRep solid model (sliced isometric projection).

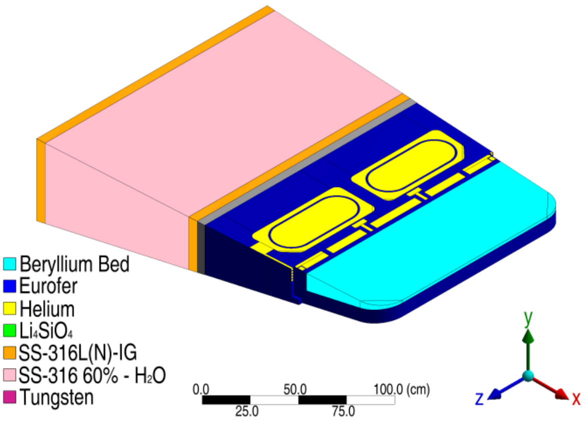

Figure 7. Simplified CAP BRep solid model (isometric projection).

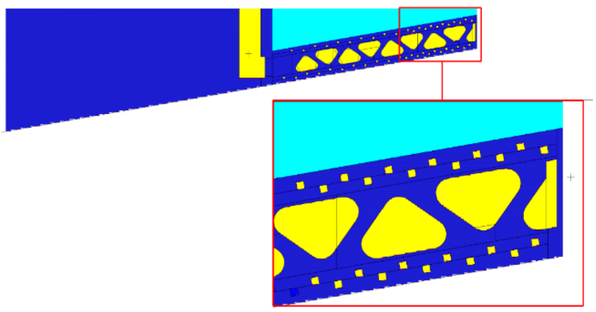

Figure 8. CAP CSG solid model (radial-poloidal view).

Again, the volumes of the BRep solid model bodies and the CSG solid model cells have been compared. A percentage difference of 0.01025% between the whole volumes of the models has been assessed together with a mean of the absolute value of the relative difference per body/cell of 0.1717%.

2.3 MODULE model

CAP and SLICE neutronic models have been joined together in order to build the solid model of DEMO HCPB BB OB4 module. The lattice features of MCNP have been used to generate the BZ, composed of a stack of 60 slice units piled in the poloidal direction and alternatively rotated. The universe features of MCNP have been used to re-create the two caps from the CAP solid model. The space between the BZ and the CAP has been filled with Be pebbles, as established by the HCPB Design Report 2015 [6]. Again, as in the SLICE model case, reflective boundary conditions both on the poloidal and toroidal planes delimiting the model have been imposed to simulate the geometrical continuity in those directions. The achieved MODULE CSG model is shown in Figure 9.

2.4 DEMO model

The MCNP model of DEMO reactor with a HCPB BB (named DEMOHCPB) is a generic geometric model taking into account a torus sector of 10° in the toroidal direction, in which the blanket has been implemented using repeated structures features with a semi-heterogeneous material composition (Figure 10 and Figure 11) [6][7].

With the aim to validate the CSG methodology, the MODULE and DEMOHCPB models have been joined together. As a first step, the OB4 module of DEMOHCPB has been voided out, then the MODULE model has been inserted in the voided space. The obtained model, DEMO, is shown in Figure 12. It consists of a 10° toroidal section model with partially homogenized blanket modules except for the OB4 module, which is represented with the full features of MODULE model.

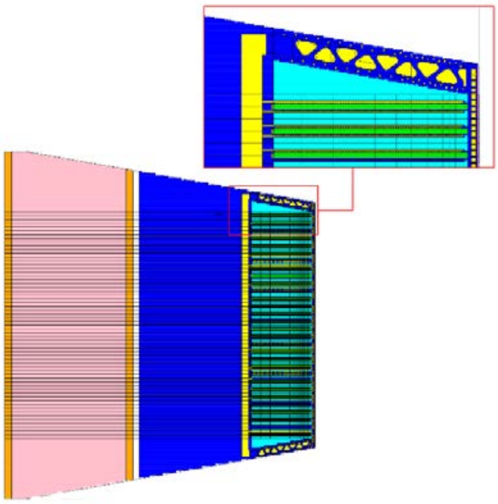

Figure 9. MODULE CSG solid model (radial-poloidal view).

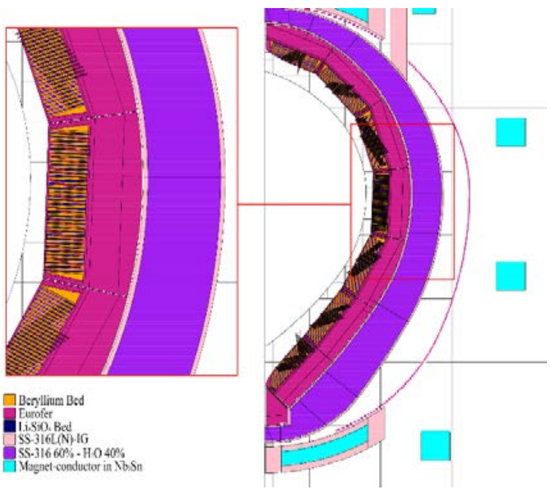

Figure 10. DEMOHCPB CSG model (radial-toroidal view) [7].

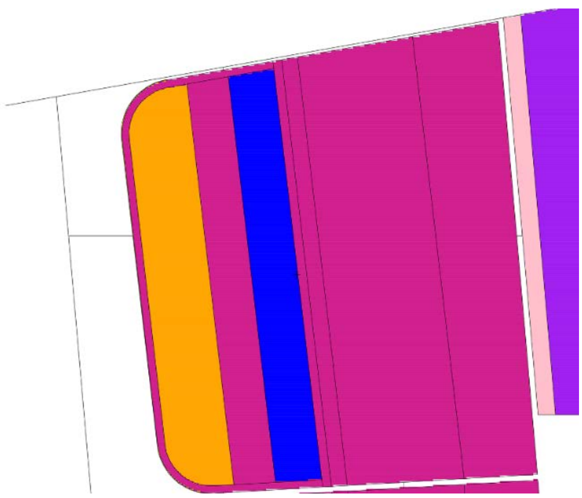

Figure 11. DEMOHCPB CSG model (radial-poloidal view) [7].

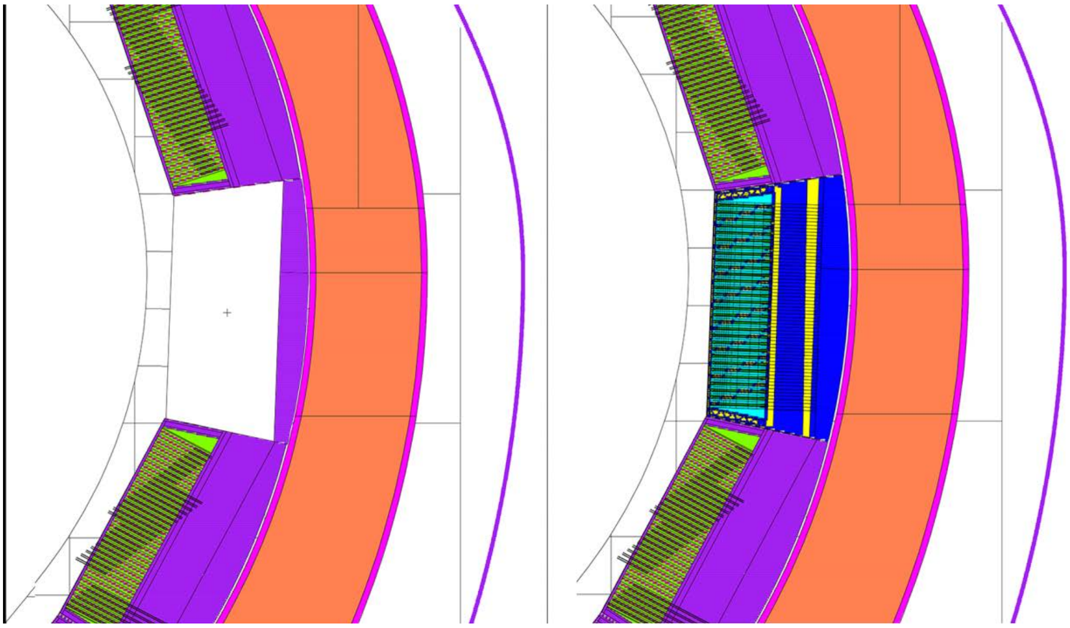

Figure 12. DEMOHCPB with voided OB4 module (left) and DEMO model (right).

3. Local sources definition

In order to perform analyses on MODULE and SLICE local neutronic models, a local source has been defined for each model with the purpose to simulate DEMO radiation conditions. For each model, a planar source has been defined, with particles emission biased in cosines and energies. A histogram distribution has been provided for particles cosines, then a dependent energy histogram distribution has been provided for each cosine bin. The emission probabilities for cosines and energies of each source have been defined starting from the results collected in an *ad hoc* analysis run with DEMO model, taking into account both neutrons coming directly from plasma and from albedo effect. As well, a photon source has been set up to take into account photons coming from neutronic interactions in other modules and scattered into the OB4 module.

The neutronic surface sources have been set up in 11 cosine bins and 99 energy bins, whilst the photonic surface sources have been segmented in 11 cosine bins and 43 energy bins. Upper limits for energy bins have been chosen in agreement with VITAMIN-J libraries group structure [10].

4. Nuclear power deposition calculation

Power deposition, Q_{dep}, on corresponding cells of DEMO, MODULE and SLICE models has been calculated and compared to validate the local source definition procedure, the boundary conditions set up and the coupling approach. Two analyses have been performed for each local model in order to acquire nuclear power deposition data. The first analysis for each model has been carried out using its local neutronic source and enabling the transport of both neutrons and photons; a second analysis has been performed with the local photonic source with the transport of photons only. Analyses have been performed considering a fusion power of 2037 MW [6]. Table 1 summarizes the obtained results for SLICE, MODULE and DEMO models showing the percentage differences with reference to DEMO value, ε_{DEMO}. From the acquired data of the deposited power on the three models a congruence emerges. The total nuclear power deposited in the domain considered is equal to 75.805 kW in DEMO and is overestimated by 0.40% in MODULE model and 2.58% in SLICE model.

Table 1. Nuclear power deposition results

	SLICE	MODULE	DEMO
Q_{dep} [W]	$7.78 \cdot 10^4$	$7.61 \cdot 10^4$	$7.58 \cdot 10^4$
ε_{DEMO} [%]	2.58%	0.40%	-

It should be noted that a better estimate of the power deposition has been obtained in the MODULE model, although SLICE and MODULE local analyses have been performed with the same procedure and the same boundary conditions. This result can be explained taking into account the influence of the bi-dimensional nature of the SLICE model. The coupling approach application and the source sampling procedure therefore allowed to obtain a reliable estimate of the overall deposited power on the local models.

5. Spatial distribution of nuclear power volumetric density deposition

Spatial distribution of nuclear power volumetric density deposition, q''', is of relevant importance in a multi-physics design cycle. The obtained power density deposition is indeed provided to thermal-mechanical codes where it is handled as an imposed load and thus it has a strong influence on design choices.

In order to score this quantity a Cartesian mesh of 2557170 tetrahedral elements (corresponding to a mesh size of 0.3 cm in all the directions) has been imposed to the SLICE model and in the corresponding region of the DEMO model as shown in Figure 13.

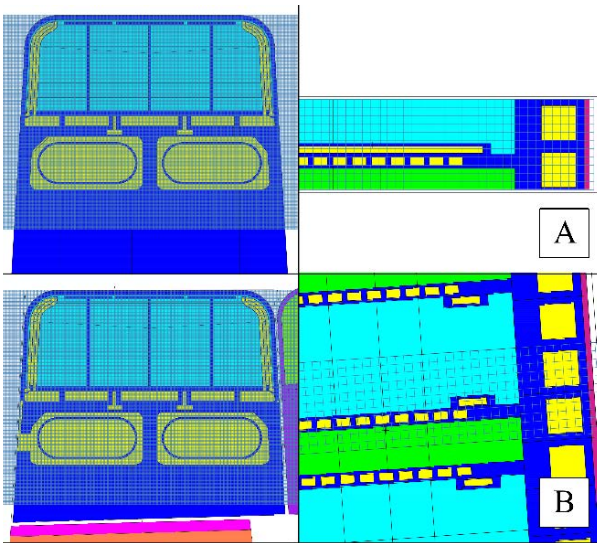

Figure 13. FMESH visualization on MCNP; A) SLICE, B) DEMO; left: toroidal-radial view, right: radial-poloidal view.

Results of neutronic and photonic mesh tallies have been summed in the SLICE model to obtain the full nuclear power density deposition in each hexahedron of the mesh.

Results show a good agreement between the models for what concerns the overall power deposition calculated from power density results. A power deposition of 76.621 kW has been achieved over the considered domain in DEMO, while the corresponding value in SLICE model is 77.492 kW, thus overestimated by 1.1376%. It can be highlighted that the achieved error for the SLICE model is lower than the analogue estimate shown in the previous paragraph in which the total nuclear power has been considered.

The spatial distribution of power density deposition in the two models is shown in a radial-toroidal view in Figure 14 and Figure 15 and in a radial-poloidal view in Figure 16.

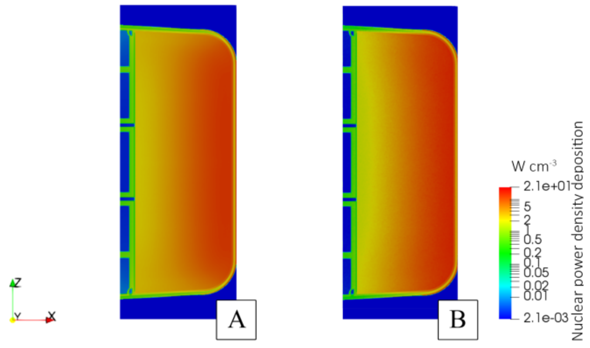

Figure 14. Nuclear power density deposition spatial distribution; A) SLICE, B) DEMO; Li_4SiO_4 bed radial-toroidal view.

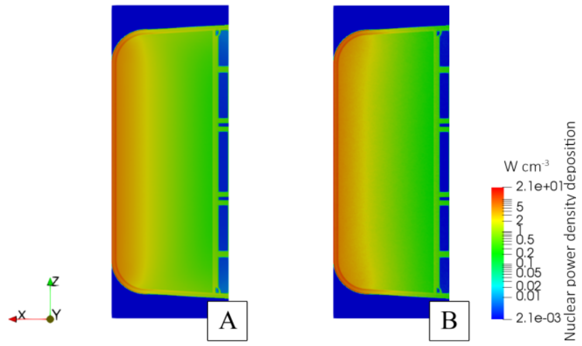

Figure 15. Nuclear power density deposition spatial distribution; A) SLICE, B) DEMO; Be bed radial-toroidal view.

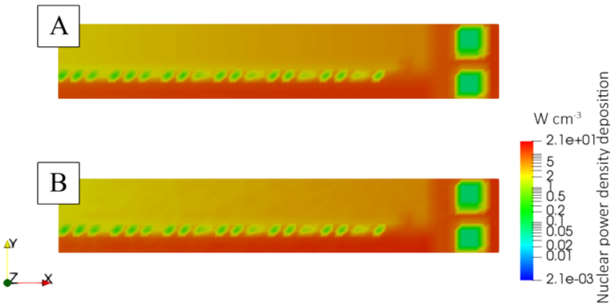

Figure 16. Nuclear power density deposition spatial distribution; A) SLICE, B) DEMO; radial-poloidal view.

For what concerns the spatial distribution of power density, a widespread agreement has been found between the responses of the analysed models. In further detail, the coincidence of the most stressed area has been assessed, although an underestimation of the maximum power density value has been discovered in SLICE model. Indeed, the maximum value in SLICE model is the 16.4867% lower than the corresponding value in DEMO model. Further improvements of the statistical behaviour of the models and a more accurate source definition may result in a better matching of local power density deposition.

The radial profile of nuclear power density deposition has been analysed evaluating the average of the power density deposition on poloidal- toroidal planes, $q'''^{*}(r)$, which is defined as in Eq.(1).

$$q'''^{*}(r) = \frac{1}{A_{pt}(r)} \int_{A_{pt}(r)} q'''(r,p,t)dA \tag{1}$$

Where $A_{pt}(r)$ is the poloidal-toroidal section of the slice which is a function of the radial coordinate only. The radial profile of such a quantity is plotted against radial coordinates in Figure 17.

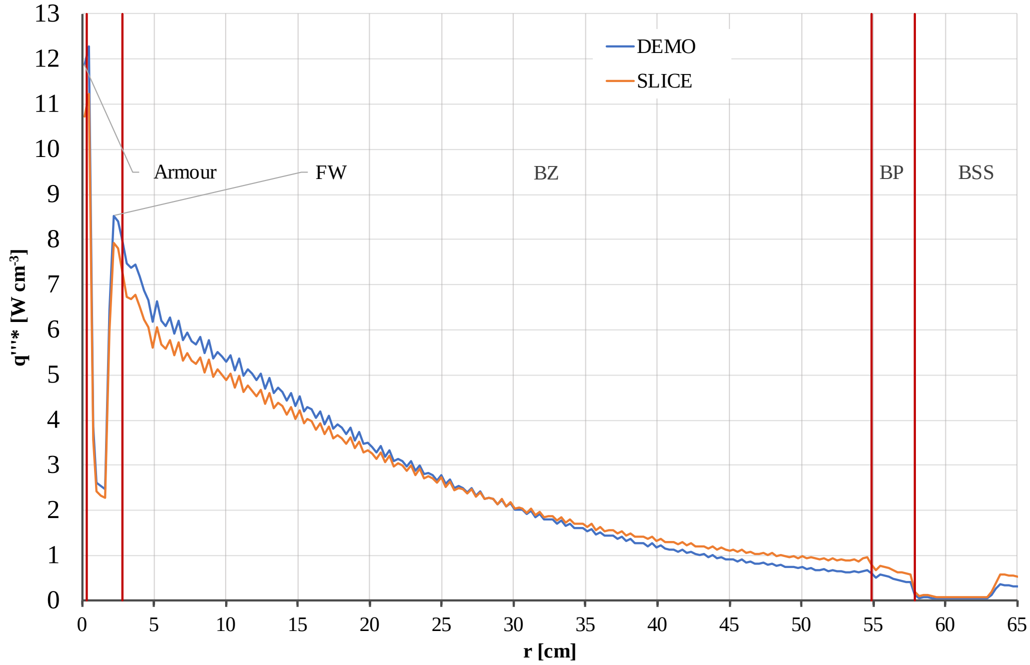

Figure 17. Radial profile of the averaged nuclear power density.

Although a shift exists between the two radial profiles of power density deposition, a congruent response of the SLICE model compared with the DEMO model can be inferred from the plot. So, it can be stated that first encouraging results have been achieved to show the consistency of the local model and the coupling procedure taken into account.

It is worthwhile to notice that the comparison between nuclear behaviour of the two different models must be further investigated to get a full insight of conditions affecting their differences in order to define potentialities and limits of the proposed coupling approach.

Conclusions

This work stems from a cooperation between University of Palermo and KIT aimed to perform the validation of the described direct coupling approach to be implemented in a multi-physics analysis tool. With this purpose, the coupling approach has been applied to the

2015 concept of DEMO HCPB BB. Three reference neutronic models, namely SLICE, MODULE and DEMO, have been set-up and analysed.

The validation has been carried out by comparing results obtained, in terms of nuclear power deposition, from the models in which the coupling approach has been used (SLICE and MODULE) and the DEMO model. As far as the total nuclear power is concerned, data obtained has shown a very good agreement. With regard to the nuclear power volumetric density, it has been observed that the response of the SLICE local model is congruent with the response of DEMO model as a consistent power density distribution has been obtained in the two models showing that the most stressed area is coincident.

The presence of some local mismatch between results makes necessary to further investigate the underlying neutronic and photonic phenomenology in order to define potentialities and limits of the coupling approach investigated. In this sense, a campaign of analysis is already on going to assess the influence of different boundary conditions in the SLICE model on its nuclear response with respect to DEMO model one, in order to further improve the overall effectiveness of the coupling procedure set up. Moreover, a parametric study on the SLICE model particle source biasing is envisaged not only to refine the aforementioned coupling method, but also to define with accuracy its limits in terms of computational effort.

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